DEPARTMENT OF NATIONAL DEFENCE

CANADA

OPERATIONAL RESEARCH AND ANALYSIS ESTABLISHMENT

DIRECTORATE OF STRATEGIC ANALYSIS

ORAE PROJECT REPORT NO. PR 508

ENVIRONMENTALISM AND ENVIRONMENTAL CHANGE AS IT AFFECTS CANADIAN DEFENCE POLICY AND OPERATIONS: PART TWO; CLIMATIC MODELLING AND ITS SIGNIFICANCE.

by

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OTTAWA, CANADA DECEMBER, 1989

THIS DOCUMENT

IS ISSUED UNDER

ORAE PROJECT 44107

ARCTIC STRATEGIC STUDIES

Approved by E. Gilman
Dr E. Gilman, Director

for CHIEF, OPERATIONAL RESEARCH AND ANALYSIS ESTABLISHMENT

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ABSTRACT

1. The greenhouse effect and the concept of global warming are well understood today, even though there is widespread ambivalence about the severity of what is to come and the time frame in which it will occur. There is concern in the scientific community that the greenhouse effect is no longer in a general state of equilibrium. This report describes current attempts to model global climate, a necessary starting point to understanding the overall problem. For the present, it is not possible to draw precise conclusions on the future state of the global system, though there is agreement on general trends and ranges. Because of climate change, Canada's Armed Forces will probably face operational problems. Globally, climate change will increase political instability and the potential for international conflict.

RÉSUMÉ

1. L'effet de serre et le concept du réchauffement de la planète sont désormais bien compris, malgré qu'il existe une certaine divergence d'opinions quant à la sévérité des effets climatiques à venir ainsi que de la periode de sursis. La communauté scientifique croit que l'effet de serre n'est plus dans un état d'équilibre. Ce rapport décrit les efforts en cours pour modeler le climat terrestre, un point de départ nécessaire pour comprendre le problème. Jusqu'à présent, il nous est impossible de conclure avec certitude l'état futur du système terrestre, bien qu'il y ait une certaine convergence d'opinions sur les directions et les limites en général. A cause de ces changements climatiques, les Forces Canadiennes rencontreront probablement des probèmes d'ordre operationnels. Globalement, les changements climatiques vont accroître l'instabilité politique et la possibilité d'un conflit international.

ENVIRONMENTALISM AND ENVIRONMENTAL CHANGE AS IT AFFECTS CANADIAN DEFENCE POLICY AND OPERATIONS: PART TWO; CLIMATIC MODELLING AND ITS SIGNIFICANCE

INTRODUCTION

1. Scientists have known about climate change and the greenhouse effect since the middle of the 19th century. A British scientist, John Tyndall first published a paper in the Philosophical Magazine in 1863 about the effect of water vapour as a greenhouse gas. In the 1890s a Swede, Svante Arrhenius, and an American, P. C. Chamberlain, both considered the problems of global warming that might result from a build up of carbon dioxide in the air caused by the combustion of coal (Gribbin, 1988).

2. Today, the greenhouse effect is a well recognized phenomenon. While it is true that the general term greenhouse effect is well understood, there is widespread ambivalence about the severity of what is to come and the time frame in which it will occur. From a policy aspect, various governmental agencies in Canada and elsewhere are having to deal with the potential consequences of the climatological changes from a practical point-of-view. The purposes of this second paper of a series on this and related subjects are several. Initially, the greenhouse effect is described, along with the anthropogenic factors that are considered to influence climate. Secondly, various types of climatic models are outlined and critically compared. This is necessary because much of the present debate is centred on which of the many forecasts is most representative of what can be expected in the early part of the 21st century. Much of the uncertainty in these models is largely due to the limited understanding of the rôle of ocean currents in the heat balance of the globe and the quantity of fossil fuels to be consumed creating energy over the next 50 years or so.

3. It is not the intent of this paper to enter the debate with new scientific data on the viability of one given climate model over another. Research scientists in various branches of climatology and meteorology are

better equipped, and are already doing so. The central focus will be to summarize their findings and arrive at an overall consensus on rates of change. The repercussions of climate change that may influence the Canadian Forces (CF) in their daily operations and in strategic planning will be discussed briefly at the end of this presentation, but these topics will be analyzed in greater detail in future papers in this series.

CLIMATE CHANGE; GENERAL PRINCIPLES

4. While for specialists much of what follows in this section is rather elementary in nature, it is incorporated in the text because it is necessary for the general reader to have a grasp of the basic concepts to be able to assess following sections. Radiant energy from the sun that strikes the earth, termed insolation (from incoming solar radiation), consists of rays of various wave lengths. The longer waves, called infrared (10^{-2} - 10^{-4} cm wavelength), are largely absorbed by the atmosphere. At the other end of the solar spectrum are the shorter, ultraviolet rays (10^{-5} - 10^{-6} cm wavelength) which are capable of producing various photochemical effects. Between these bands of invisible radiation is the visible portion of the spectrum known as sunlight. It is the most effective in heating the earth. When rays of the solar spectrum reach the earth they are partially absorbed and converted from short-wave to long-wave radiant energy or heat (Fig. 1). Energy gained in this way provides the fuel for the process of weather and climate.

5. By virtue of its absorption and conversion of insolation into heat, the earth itself becomes a radiating body. Although the components of the atmosphere collectively are able to absorb only a small portion of the incoming short-wave radiation, they can capture a large part of the outgoing long-wave radiation. Water vapour and carbon dioxide are especially effective at absorbing long-wave energy as are less common gasses such as chlorofluorocarbons (CFCs), nitrous oxides, ozone and methane. In fact, CFCs, best known as the chemicals responsible for the holes in the ozone layer over the Antarctic are very efficient greenhouse gasses. One molecule of either of the two most common CFCs has the same greenhouse warming effect as 10,000 molecules of carbon dioxide.

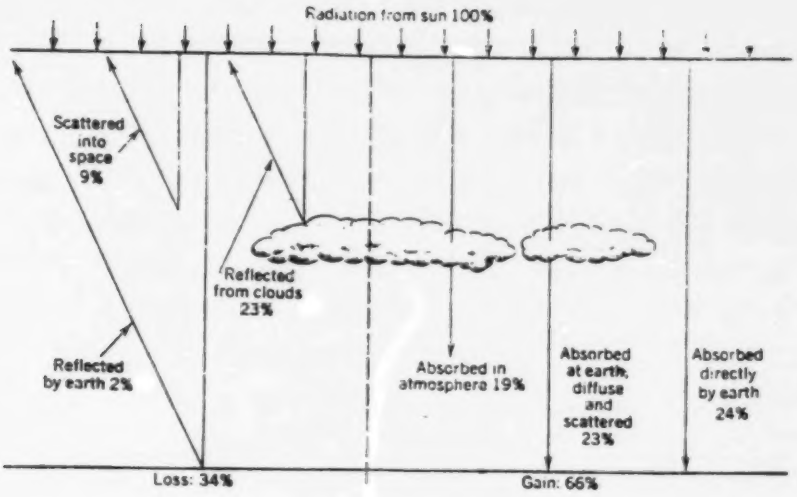
Radiation from sun 100%
Scattered into space 9%
Reflected from clouds 23%
Reflected by earth 2%
Absorbed in atmosphere 19%
Absorbed at earth, diffuse and scattered 23%
Absorbed directly by earth 24%
Loss: 34%
Gain: 66%

Fig. 1 Heating of the earth and its atmosphere by insolation (Critchfield, 1966).

6. The ability of the atmosphere to admit most of the insolation and retard the re-radiation from the earth's surface is termed the greenhouse effect, and if it did not exist, the earth would become alternately very hot or cold. There is a heat deficit at high latitudes and a surplus at low latitudes owing to radiation gains and losses associated with differences in solar insolation. Horizontal transportation by winds and water in atmospheric and ocean currents prevents the progressive accumulation of heat in equatorial regions. The greenhouse effect maintains global surface temperatures at an average of 288 K or 15°C, which is about 35°C warmer than it would be if the mechanism did not exist (Hare, 1988). It should be remembered that the greenhouse effect has positive, desirable consequences, as long as it remains stable and within the general range under which life evolved. The current problem is more related to the rate of change of the greenhouse effect, its impact on weather and climate, and how we adjust. (As Gribbin (1988) comments, this is still a more desirable state of the world, from a human adjustment point-of-view, than the onset of a new Ice Age might be.)

7. Although part of the net radiation gained by the earth's surface is transferred upward by long-wave radiation and as sensible heat by the processes of convection and conduction, much of it reaches the atmosphere as latent heat in water evaporated from land and water surfaces, and especially from oceans. Moist air masses may move great distances before condensation of their water vapour releases huge quantities of latent heat. The processes of heat transfer maintain a complex exchange between the earth's surface and the atmosphere, but ultimately, the total amount of energy coming to the earth is equalled by total outward losses to space.

8. This having been said, there is concern in the scientific community that the greenhouse effect is no longer in a general state of equilibrium; that in fact, the atmosphere of the earth is warming at a faster pace than has been previously documented in recorded or recent geologic history. Greenhouse gasses are increasing at significant rates. For example, carbon dioxide is now increasing at 4% per decade, methane is increasing at 1.5% per decade, chiefly from fossil fuel burning, and other gasses - primarily nitrous oxides and various synthetics, the CFCs - at lower rates (Hare, 1988). Measurements taken at Mauna Loa, Hawaii, a major international study site, show that carbon dioxide concentration has increased from 316 parts per million by volume (ppm) in 1959 to 342 ppm in 1983, an 8% increase in 24 years. A variety of direct carbon dioxide measurements and indirect reconstructions indicate that the pre-industrial carbon dioxide concentration during the period from 1800 to 1850 was 210± ppm. Projections of future usage of fossil fuels indicate that concentration could reach twice the pre-industrial values some time during the 21st century (Schlesinger, 1986).

9. The depletion of ozone over the Antarctic and the resultant impact of enhanced ultraviolet radiation on the highly productive ecosystem of the circum-Antarctic ocean, may have implications for the release of carbon dioxide from the ocean to the atmosphere. Most of the ocean's carbon is present in cold, fairly stagnant water at depth, having arrived there by the action of microscopic life forms, plankton. Plankton acts as a pump, extracting carbon dioxide from the air and depositing it on the sea floor. Carbon dioxide then

returns to the atmosphere in association with a slow upwelling motion at low latitudes. While the surface waters cool and sink at high latitudes, they draw carbon from the atmosphere, roughly balancing the source at low latitudes. Falling fecal matter provides an additional important means for transporting carbon from the surface to the deep. Any thinning of the ozone layer at high latitudes may kill plankton in these sensitive areas, thereby reducing the effectiveness of the biological pump; this will lead to even more carbon dioxide in our atmosphere and further global warming.

CLIMATIC MODELLING

10. The predictions of enhanced concentrations of greenhouse gasses have significant consequences for global warming and changing climate. Various scenarios have been developed over the past few decades via palaeoclimatology (that branch of the science which studies climatic trends in the distant past) and numerical, climatic modelling. These are used to predict the impact of the changes that are likely to occur on a global and regional basis. Evidence from past climates is limited in its application to scenarios for the future because the type of climate forcing, rate of change, and magnitude may not be as extreme as the currently expected warming. Moreover, the quality of a reconstruction decreases through time, and it may not be possible to reproduce all critical climatic variables (Schlesinger, 1984). Recently, a hierarchy of climatic models has been developed, ranging from simple, zero-dimensional, energy balance models (EBMs) to the more sophisticated, three-dimensional, general atmosphere-ocean coupled circulation models (GCMs).

Energy Balance Models (EBMs)

11. The EBMs compute the change in temperature at the earth's surface as functions of incoming and outgoing radiation, radiation and latitude, and radiation and altitude. The radiative processes and effects due to mean atmospheric motions are usually simplified and parameterized. These types of models are capable of demonstrating the sensitivity of the climate to various interactive processes such as those between temperature, ice cover and albedo, or between clouds and radiation. However, these models cannot distinguish

between north or south climates or give any indication of the frequency of events such as storms.

Radiative-Convective Models (RCMs)

12. RCMs are normally one dimensional in the vertical and compute the effects of variation in temperatures with changing altitude by incorporating solar and radiative heat fluxes. These types of models are limited to calculating global and annual averages, and contain simplistic convective parameterization without including atmospheric thermodynamics. One important feedback in RCMs involves atmospheric water vapour in a cloud-radiation loop. This style of model predicts that an increasing atmospheric carbon dioxide content results in a warming of the troposphere (0-12 km altitude) and a cooling of the higher stratosphere (12-50 km altitude).

General Circulation Models (GCMs)

13. Because many aspects of climate, such as the horizontal transport of heat and land/sea contrasts, are omitted in RCMs and are inadequately treated in one and two dimensional EBMs, considerable effort of late has been applied to the development of GCMs. GCMs are, in essence, an enhancement of numerical weather prediction models; three dimensional numerical models of the atmosphere with which the state of the atmosphere can be completely described as a function of time and place (Van der Veen, 1986). They are based on computations of atmospheric winds (equations of motion), radiative transfer and heating (thermodynamic equation), water vapour (hydrological cycle with evaporation -source and precipitation -sink; equation of atmospheric water) and cloud formation; they are described as Atmospheric GCMs or AGCMs. More recent advanced models incorporate ice albedo/temperature feedback and coupling to oceanic models (Eybergen and van Huis, 1989). These are termed Atmospheric-Ocean Coupled GCMs or AOGCMs. An important basic characteristic of GCMs is that they are not and cannot be used for prediction purposes, rather they show the circulation of the atmosphere around the globe under equilibrium conditions (typical of 10 years of record, for example). The structure and processes of GCM climate models is shown in Fig. 2. For a more detailed numerical analysis of GCMs the reader is referred to Schlesinger and Mitchell (1985).

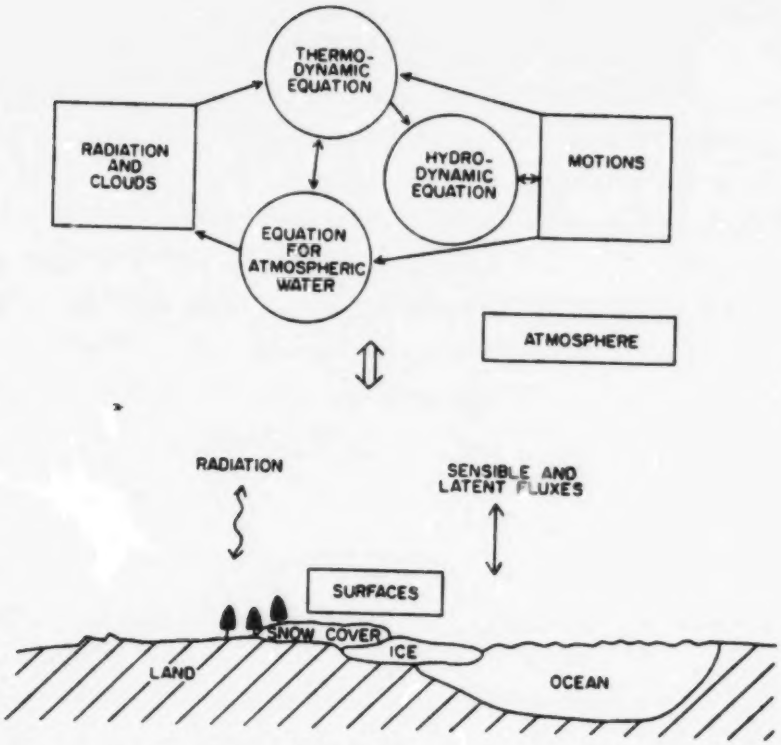

Fig. 2 Schematic description of the structure and processes of GCM climate models (after Dickenson, 1986).

14. According to Bach (1988), several of the small processes important to climate are not explicitly resolved due to the limited spatial resolution (about 400km) of GCMs. The usual procedure is to parameterize them, i.e., to relate them either statistically or empirically to the scale of those variables which are resolved. The small scale processes which are parameterized include transfer of solar and terrestrial radiation, turbulent transfer of heat, and momentum between the earth's surface and the atmosphere and within the atmosphere, as well as condensation of water vapour. The physical processes and parameterization schemes differ between the various GCMs which accounts for some of the differences in the results.

15. The simulation of climatic change with a GCM requires the prescription of certain parameters and boundary conditions such as the solar constant and earth/sun orbital parameters, land/sea distribution and topography, total atmospheric mass and composition, etc. Moreover, the earth's climate cannot be accurately simulated without coupling the atmosphere with the ocean, the ice and the biosphere. The ocean has a significant influence on climate because of its large heat storage capacity. Special attention is required for the computation of sea surface temperature since it is determined by ocean circulation and the energy exchange between ocean and atmosphere. So far, most of the present GCM's have only a rudimentary incorporation of the ocean effect (Bach, 1988).

16. After a GCM's parameterization and boundary conditions have been set, the rates of change of the prognostic variables are determined for a global network at either discrete grid points , as in grid point or finite difference models, or by a finite number of prescribed mathematical functions, as in spectral models. The variables at the grid points are then integrated forward in time in discrete steps starting from some initial value. The choice in time steps, ranging from 10 to 40 minutes, depends on the grid size, the speed of movement of weather disturbances, and the integration method. Depending on the model and its initial conditions, integration may take from a few months (without the ocean effect) to several years (with ocean-atmosphere coupling) before the model reaches its equilibrium climate, i.e., when its time-averaged statistics are no longer perceptibly changing. The statistics of such a control integration (the control run) define the model's climate. This can be compared with the observed, such as in model validation, or with a perturbed climate, such as for a carbon dioxide doubling.

17. The climate modelling group of the Canadian Climate Centre (CCC) has recently completed a 2 X CO_2 experiment with its GCM. The design of the Canadian GCM is comparable to others in use for climate change studies. However it provides a somewhat higher resolution, providing at least twice the information density of other published results. Other features include a

parameterization of how the reflective and absorptive properties of clouds change as temperatures change, the incorporation of full annual and daily solar heating cycles, and specification of ocean transport to allow better simulation of ocean temperatures and ice boundaries. As with other models, the ocean treatment is still very simplified.

18. Table 1 summarizes some of the criteria for most of the U.S. and U.K. GCMs that have been used in carbon dioxide sensitivity studies. The models differ from each other in computational resolution, experimental design, and certain physical parameterizations including radiative transfer, precipitation, and cryospheric dynamics (Hengeveld, 1987). Despite their differences, in general, to be successful, the models should:

1. be based on realistic geography and topography;
2. have high spatial resolution;
3. have an adequate temporal resolution;
4. incorporate a coupled model of the ocean-atmosphere circulation, and;
5. simulate realistically the patterns of observed climate.

19. None of the present GCMs in Table 1 meets all of the requirements listed above, but there are differences in the currently available models that make them useful for impact analysis. A somewhat realistic topography and geography with a global domain is a prerequisite in impact studies. Particularly for agricultural impact analysis, both an annual and diurnal cycle is essential so that the swamp models (a perpetually wet land, of zero heat capacity without any heat transport and with an infinite water vapour source.) and mixed layer ocean models are less useful. The climatological ocean models with prescribed sea surface temperature and sea ice cover for a carbon dioxide doubling result in a surface temperature increase that is about an order of magnitude lower than that obtained from more realistic modelling

Table 1

Criteria for and Characteristics of General Circulation Models Used in CO_2 - Induced Climate Change Studies (after Bach, 1988)

Model/ Researcher	Geography	Topography	Spatial Resolution	Annual Cycle/ Diurnal Cycle	Ocean/Sea Ice	CO_2 Simulation	Temperature increase(K) due to CO_2[a]
(1) GFDL Manabe, Wetherald (1975)	Idealized land/ ocean	None	V:9 layers H:Eq. to 81.7^0 A = 120^0 sector dB = variable dA = 6^0	No/ no	Swamp (no heat capacity or transport)/ice cover predicted	2 x CO_2	2.9
(2) GFDL Manabe, Wetherald (1980)	Idealized land/ ocean	None	V:9 layers H:Eq. to Pole A = 120^0 sector dB = 4.5^0, dA = 5^0	No/ no	Same as (1)	2 x CO_2	3.0
(3) GFDL Manabe, Stouffer (1980); Manabe, Wetherald Stouffer (1981)	Realistic	Realistic	V:9 layers H:Pole to Pole B = 360^0 (spectral)	Yes/ no	68 m mixed layer (no horizontal heat transport)/ice thickness predicted	4 x CO_2	4.0
(4) OSU Gates, Cook, Schlesinger (1981)	Realistic	Realistic	V:2 layers H:Pole to Pole dB = 4^0 dA = 5^0	Yes/ yes	"Climatological ocean", sea surface temp. prescribed/ice cover prescribed	2 x CO_2 4 x CO_2	0.2 0.4
(5) OSU Schlesinger (1983)	Realistic	Realistic	Same as (4)	No/ no	Swamp (no heat capacity or transport)/ice cover predicted	2 x CO_2	2.0
(6) NCAR Washington Meehl (1983)	Realistic	Realistic	V:9 layers H:Pole to Pole A = 360^0(spectral) dB = 4.5^0, dA = 7.5^0	No/ no	Same as (5)	2 x CO_2 2 x CO_2	1.3[b] 1.4[c]
(7) NCAR Washington Meehl (1984)	Realistic	Realistic	Same as (6)	Yes/ no	50 m mixed layer (no ocean heat transport)/ ice cover predicted	2 x CO_2	3.5

Table 1 (cont'd)

Criteria for and Characteristics of General Circulation Models Used in CO_2 - Induced Climate Change Studies (after Bach, 1988)

Model/ Researcher	Geography	Topography	Spatial Resolution	Annual Cycle/ Diurnal Cycle	Ocean/Sea Ice	CO_2 Simulation	Temperature increase(K) due to CO_2[a]
(8) UKMO Mitchell (1983)	Realistic	Realistic	V:5 layers H:Pole to Pole A = 360°,330km	Yes/ yes	"Climatological ocean", sea surface temperature prescribed + 2 K/ice	2 x CO_2	0.2
	Realistic	Realistic		Yes/ yes	cover prescribed	2 x CO_2	2.2
(9) UKMO Mitchell, Lupton (1984)	Realistic	Realistic	Same as (8)	Yes/ Yes	Sea surface temperature prescribed + lat. varying increment, ice cover predicted	4 x CO_2	4.5
(10) GISS Hansen et al. (1984)	Realistic	Realistic	V:9 layers H:Pole to Pole A = 360° dB = 8° dA = 10°	Yes/ yes	60-70 m mixed layer with prescribed seasonal depth and prescribed horizontal transport/ice thickness predicted	2 x CO_2	4.2
(11) OSU Gates, Potter (1985)	Realistic	Realistic	Same as (4)	Yes/ Yes	Variable-depth mixed layer	2 x CO_2	1.5
(12) OSU Gates et al. (1984) Schlesinger et al. (1985)	Realistic	Realistic	Same as (4)	Yes/ Yes	Complete ocean GCM	2 x CO_2	1.5

V = vertical resolution; H = horizontal resolution; A,B: latitude, longitude. GFDL: Geophysical Fluid Dynamics Laboratory, Princeton, USA; GISS: Goddard Institute for Space Studies, New York, USA; NCAR: National Center for Atmospheric Research, Boulder, USA; OSU: Oregon State University, Corvallis, USA; UKMO: Meteorological Office, Bracknell, UK. Source: Adapted from Schlesinger (1983) and updated.

[a] Global mean equilibrium temperature at the surface (some of the models may not have run long enough to have reached equilibrium).
[b] Clouds (prescribed).
[c] Clouds (predicted).

with feedbacks between the atmosphere and ocean (Bach, 1988). Since most planners will be concerned with climate change over the next fifty years (near-term impacts), models that deal with a quadrupling of atmospheric carbon dioxide are less useful than those that simply double the amount of gas present. The former serve only to enhance the statistical reliability of predictions. Extensive sensitivity experiments have shown the desirability of using higher spatial resolution and the need for improvements in various modelling processes (Hansen et al., 1984).

Analysis of Model Reliability

20. It is not possible to draw precise conclusions on the future state of the global system, especially on a zonal mean scale, from existing climate models. This is because of the degree of uncertainty or error of estimation in current models. The greatest uncertainty introduced to model results occurs not only from the low spatial resolution, but from the inadequate inclusion of surface water budgets (atmosphere-surface exchanges), advection cloud characteristics (low-latitude cirrus, high-latitude stratus), ocean dynamics (probably the most significant gap), and the spatial variation of snow and ice cover. In a high-latitude climate such as Canada's north, snow cover is a very significant factor in the hydrological cycle and the ground thermal regime, affecting the growth of vegetation and the characteristics of permafrost.

21. Modelled oceanic, cryospheric, and land surface components tend not to be as highly developed as their atmospheric counterparts, since they represent slowly-acting processes and because there are fewer observations from which to develop parameterizations (Gates, 1981). A good example is El Niño, a poorly understood oceanographic event in the Pacific that occurs once every four or so years in which winds and currents are reversed for a few months with dramatic effect on fish, birds and people. It has complicated and uncertain links to the greenhouse effect and climate change. The biosphere, however, is the most ignored component of the global climate system. Although biomass changes have been portrayed in various land-surface models, the lack of any vegetation cover (important at any scale in surface energy and water exchan-

ges, soil moisture, albedo, evapotranspiration, reflectivity, and as a carbon source or sink) in GMCs is recognized as a major deficiency (Hengeveld, 1987).

22. Along with the Canadian Climate Centre model, carbon dioxide sensitivity simulations of the climatic system have been developed at the U.K. Meteorological Office (UKMO), Bracknell; the National Center for Atmospheric Research (NCAR), Boulder, USA; the Godard Institute for Space Studies (GISS)/NASA, New York; in addition to the Geophysical Fluid Dynamics Laboratory (GFDL)/ NOAA, Princeton (Table 1). A comparison of GCM results shows close agreement in projections for carbon dioxide-induced global warming, especially if differences between model descriptions of feedback processes are ignored (Hengeveld, - 1987). Swamp ocean models tend to show a larger range in magnitude of change than mixed-layer GCMs.

23. In general, the carbon dioxide-induced changes in the zonal mean temperatures simulated by these atmospheric GCM/mixed layer ocean models for December-January-February (DJF) and June-July-August (JJA) display features similar to those simulated by the atmospheric GCM/swamp ocean models for annual mean insolation. In particular, the temperature changes in both seasons are negative in the stratosphere above 20 km and are positive in the lower stratosphere, and troposphere. At the surface, the stratospheric cooling increases with altitude during both seasons, the tropospheric warming increases with altitude between about 30°S and 30°N in DJF and between about 40°S and 90°N in JJA, and the surface warming increases from the tropics to the higher latitudes in the winter hemisphere in both seasons and also during the summer in the Southern Hemisphere. The changes in the annual cycle of zonal mean surface air temperature show little variation between 50°S and 30°N, and a large seasonal variation poleward of 50° latitude in both hemispheres (Fig. 3). The geographical distributions of the carbon dioxide induced surface air temperatures changes also exhibit a qualitative similarity in that the location of the maximum winter warming occurs in the high latitudes of both hemispheres where the sea ice has retreated poleward. The global mean surface air temperature given by three of the most recent

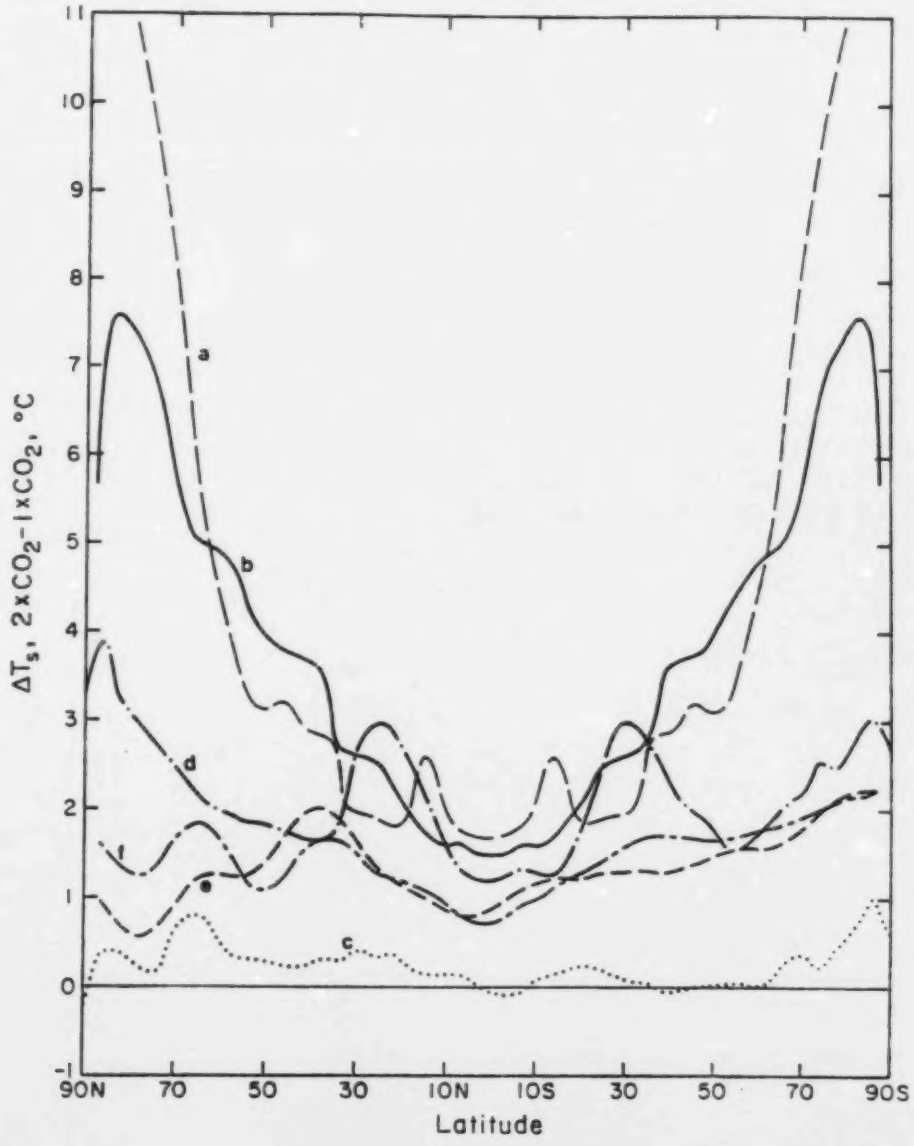

Fig. 3 Zonal mean surface temperatures (after Schlesinger, 1986)

simulations ranges from 3.4 to 4.5°C which is considerably narrower than the 1.3 to 3.9°C range given by the earlier GCM/swamp ocean models (Table 1). Swamp models have the disadvantage of not including horizontal heat transport, only vertical. Therefore, there would likely be a narrower range of equilibrium temperatures than with true ocean models.

24. According to Schlesinger (1986), although the latest studies show considerable quantitative agreement in their simulated mean surface air temperature changes, they also show substantial disagreement in their simulated zonal mean temperature changes. Furthermore, the simulated geographical distributions exhibit large differences in both the magnitude and seasonality of the regional surface air temperature changes.

25. The most recent simulations of climate change induced by a doubling of the carbon dioxide concentration each exhibit an increase in the global mean precipitation rate with values that range from 7.1% to 11.0% of their respective current values (Fig. 4). Schlesinger (1986) contends that there is a relationship between the magnitude of the increases in the global mean precipitation rates and surface temperatures. This is likely the result of the temperature dependence of the water vapour saturation pressure. In particular, both positive and negative changes in precipitation rates are exhibited with the largest changes generally occurring between 30°S and 30°N. Precipitation changes poleward of these latitudes are generally positive during both DJF and JJA over both ocean and land, with increases less than 1mm/day occurring over the northern hemisphere continents and Antarctica during both seasons. But, despite these agreements, substantial regional differences exist. For impact purposes, one should note that soil conditions and runoff to rivers is of more importance than precipitation estimates. There is only measured scientific confidence in precipitation estimates from GCMs due to the smaller scale processes involved (unlike temperature).

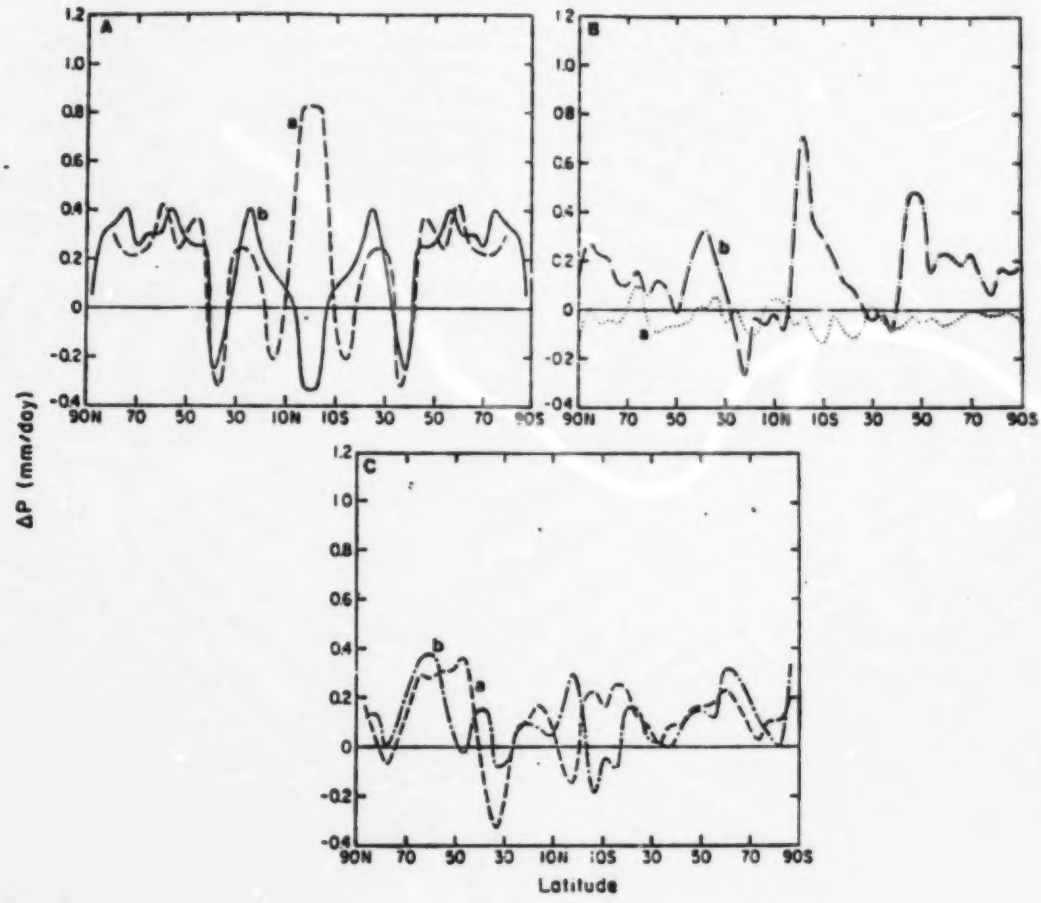

Fig. 4 The change in zonal-mean precipitation rate simulated by six GCMs for doubled carbon dioxide. The data of (A) Manabe and Wetherald (1975, curve a; 1980, curve b) are plotted symmetrically about the equator. (B) Data from Gates et al. (1981, curve a) and Schlesinger (1983, curve b). (C) Data from Washington and Meehl (1983): curve a: predicted clouds; curve b, prescribed clouds. (From Schlesinger, 1984).

SUMMARY AND CONCLUSIONS

26. It is important that we do not expect too much from GCM-based or other scenarios of climate in a high carbon dioxide world. The models are, at their present state of development, only able to provide us with internally consistent pictures of a plausible future climate which may be used to evaluate the possible range of impacts of carbon dioxide-induced climatic change on society. A general consensus is that the annual global average temperature will rise from the 1950-80 value of 15.3°C to 16.8-19.8°C by the year 2035. Furthermore, the short term variability of weather patterns at any one location may increase markedly as the flux in temperature increases spatially.

27. The largest sources of uncertainty in modelling global average temperature change appear to be the feedback from oceans, clouds, ice-albedo, and possibly lapse rate and water-vapour changes. The most important of these, storage of heat in the oceans, delays the magnitude warming presently expected for an equilibrium response to carbon dioxide heating (and that of other trace gases) and may significantly modify the geographical distribution of climatic change. There is qualitative agreement among all current three-dimensional models that largest equilibrium temperature increases would occur in regions of high latitude winter. There is some but not compelling evidence for mid-latitude, mid-continent summer drying. Soviet palaeoclimatologists, for example, state that the world will become generally wetter as well as hotter (Miller and Pearce, 1989). The Soviet Union and Canada should benefit most. A few Western climatologists are sceptical about these predictions. According to some numerical modallers, only high-latitude precipitation increases in winter are likely (Dickenson, 1986).

28. Despite the differences on detail, there is general agreement on most of the mechanisms and directions of climate change that are likely to occur within the next fifty years. From a national point-of-view, Canada's Armed Forces will probably have to face the following types of operational problems;

a. ship and submarine operations along the east coast and the Arctic (both having a longer iceberg season reaching further south), and rising water depths in most harbours will result in new operations planning. DND infrastructure may have to be heavily modified;

b. air traffic, especially in the Arctic, where runways may have to be completely rebuilt and flight operations be redesigned, will change considerably as meteorological conditions become more highly variable both in severity and frequency;

c. land aspects such as mobility in areas of degraded permafrost due to climate change will be more difficult. Required infrastructure in the Arctic and in newly settled areas in the south, brought about by migrating populations, will be expensive and time consuming. The availability of fresh water for various DND establishments may be problematic.

29. On a global scale, according to the final statement from the Toronto Conference on the Changing Atmosphere: Implications for Global Security, which was held in June, 1988, climate change will:

a. imperil human health and well-being;

b. diminish global food security, through increased soil erosion and greater shifts and uncertainties in agricultural production, particularly for many vulnerable regions;

c. change the distribution and seasonal availability of fresh water resources;

d. increase political instability and the potential for international conflict;

e. jeopardize prospects for sustainable development and reduction of poverty;

f. accelerate extinction of animal and plant species upon which human survival depends;

g. alter yield, productivity and biological diversity of natural and managed ecosystems, particularly forests.

The Conference also recommended that a reassessment of nuclear energy take place in an effort to wean the globe from CO_2 -producing fuels. This could be of significance to the CF in planning future ship designs.

30. For those involved in international security issues, both operators and analysts, this is an almost overwhelming catalogue of problems, and one that goes far beyond the more traditional geopolitical events that are normally dealt with. The literature summarized in this paper is a good indication of the seriousness that the scientific community attaches to the issue. Future papers in this continuing series will address specific climate change-related problems such as permafrost degradation, changing sea levels, shifting agricultural zones and water resources (both on a continental and global scale). These will be of direct concern to the long range operations and policy planners at DND. In many respects the issues are of equal importance to our partners in NATO and could well form the basis of a joint Alliance study.

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